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WACŁAW DZIURZYŃSKI*, ANDRZEJ KRACH*, TERESA PAŁKA*

COMPUTER SIMULATION OF THE PROPAGATION OF HEAT IN ABANDONED WORKINGS INSULATED WITH SLURRIES AND MINERAL SUBSTANCES

SYMULACJA KOMPUTEROWA ROZPRZESTRZENIANIA SIĘ CIEPŁA W ZROBACH IZOLOWANYCH ZA POMOCĄ ZAWIESIN ORAZ SPOIW MINERALNYCH

In the paper the results of investigations aimed at further identification of the phenomena occurring in abandoned workings and connected with the flow of air-gas (methane, carbon dioxide, nitrogen, oxygen and carbon oxidation products) mixture with taking into consideration the impact of supplied mineral substances on the processes of self-heating of the coal left in goaves were presented. The known and successfully used method for the prevention of fires in abandoned workings is the technology of filling goaf with an ash-air mixture, which also raises the issue of the effective use of that mixture. The computer, i.e. digital simulation methods being developed and intended for the purpose of the process discussed here are a good complement of the use of that technology. A developed mathematical model describing the process of additional sealing of gob with wet slurry supplied with three pipelines is based on the balance of volume of the supplied mixture and contained in the body created in goaves. The form of that body was assessed on the basis of the observation results available in literature and the results of model investigations.

The calculation examples carried out for the the longwall area and its goaf ventilated with the "U" system allow to state that the introduced modification of the mathematical model describing the flow of the mixture of air, gases, and wet slurry with consideration of the coal burning process in the fire source area was verified positively. The digital prognostic simulations have confirmed a vital impact of the wet slurry supplied into the goaf on the processes of coal burning and also the change of rate and volume flow rate of the air mixture in goaf. As a complement to the above it should be noted that such elements as the place of the slurry supply in comparison with the longwall inclination or fire source area location is of great importance for the effectiveness of the fire prevention used. The development of computer/digital simulation methods requires further investigations of the model adopted in this study. Those investigations should be aimed at making credible the theoretical model of the mixture flow through porous medium and the supplied mineral material. Such investigations will allow to verify the body form based on the mixture parameters such as humidity, viscosity, and fluidity and depending on the properties of the porous medium. Further development of the modelling of the phenomena discussed in this paper should be based on the methods of use of the description of the flow of fluids and slurry on the basis of 3D models.

Keywords: longwall goaf, digital simulation, fire hazard, inlet mineral substances

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* STRATA MECHANICS RESEARCH INSTITUTE OF POLISH ACADEMY OF SCIENCES, UL. REYMONTA 27, 30-059 KRAKOW, POLAND

W artykule przedstawiono wyniki badań prowadzące do dalszego poznania zjawisk zachodzących w zrobach związanych z przepływem mieszaniny powietrzno-gazowej (metan, dwutlenek węgla, azot, tlen i produkty utleniania węgla) z uwzględnieniem wpływu podawanych substancji mineralnych na procesy samozagrzewania pozostawionego w zrobach węgla. Znaną i stosowaną z powodzeniem metodą zapobiegania pożarom w zrobach jest technologia wypełniania zrobów mieszaniną popiołowo – wodną, co wiąże się również z zagadnieniem efektywnego jej stosowania. Rozwijane metody komputerowej symulacji rozważanego procesu dobrze uzupełniają jej stosowanie. Przedstawiono rozbudowany model matematyczny opisujący proces doszczelniania zrobów poprzez podanie za pomocą trzech rurociągów wilgotnej zawiesiny, bazuje na bilansie objętości mieszaniny doprowadzonej i zawartej w bryle utworzonej w zrobach. Kształt tej bryły oszacowano na podstawie dostępnych w literaturze wyników obserwacji i wyników badań modelowych.

Wykonane przykłady obliczeniowe dla rejonu ściany i jej zrobów przewietrzanej system na „U“, pozwalają stwierdzić, że dokonana modyfikacja modelu matematycznego opisującego przepływ mieszaniny powietrza, gazów i wilgotnej zawiesiny z uwzględnieniem procesu palenia węgla w ognisku pożaru została pozytywnie zweryfikowana. Wykonane komputerowe symulacje prognostyczne, potwierdziły istotny wpływ podawanej wilgotnej zawiesiny do zrobów na procesy palenia węgla jak również na zmiany prędkości i strumienia objętości przepływu mieszaniny powietrza w zrobach. W uzupełnieniu powyższego należy zauważyć, że takie elementy jak miejsce podania zawiesiny w stosunku do nachylenia ściany czy lokalizacji ogniska pożaru ma duże znaczenie dla skuteczności zastosowanej profilaktyki pożarowej. Rozwój komputerowej symulacji wymaga eksperymentalnych badań celem uwiarygodnienia przyjętego w niniejszej pracy teoretycznego modelu przepływu mieszaniny i podawanych substancji mineralnych przez ośrodek porowaty. Badania takie umożliwią weryfikację kształtu bryły w zależności od parametrów mieszaniny takich jak wilgotność, lepkość i rozlewność oraz od własności ośrodka porowatego. Dalszy rozwój modelowania omawianych w artykule zjawisk winien opierać się na metodach zastosowania opisu przepływu płynów i zawiesiny w oparciu o modele trójwymiarowe.

Słowa kluczowe: zroby ściany wydobywczej, symulacja cyfrowa, zagrożenie pożarowe, wlotowe substancje mineralne

1. Introduction

The paper presents the result of researches leading to the development of a mathematical description of the phenomena occurring in abandoned workings connected with the flow of air-methane mixture flow (methane, carbon dioxide, nitrogen, oxygen, and carbon oxidation product) with the consideration of the mutual impact of the supply of mineral substances on the processes of self-heating up of the coal left in abandoned workings which lead to the formation of fire source area in goaf. The development of mathematical models allows to observe the transport of heat in goaf with the indication at the same time of the impact of the slurries being fed on the variations of temperature distribution and concentrations of gases as well as the flow directions in goaf and longwall-side workings. This creates a basis for the development of a computer method which makes it possible to assess the effects of the supply of slurries to goaf and its impact on the processes of spreading of the fire in abandoned workings depending on the change in the permeability and porosity distribution in the considered area.

The intensification of coal mining in Polish coal mines causes a significant risk of endogenous fires and methane hazard still existing in the gob of the longwalls mined with the roof-collapse technique. The known and successfully used method of fire prevention in abandoned workings is the technology of filling old abandoned workings up with ash-water mixture, and this is connected with the issue of effective use of this method. The computer methods of the simulation of the process in question, which are still being developed, constitute a good complement of the use of this simulation.

2. The mathematical model of the process of additional sealing of abandoned workings

In the process of additional sealing of goaf with ash-water mixtures, a gradual change of the air migration through those workings occurs. It is connected with the progressive filling up of the porous environment of the goaf with the supplied mixture. It is also possible to supply inert gases to abandoned workings by the use of carbon dioxide in fire prevention procedures and the assessment of its effective impact on the supplied slurry and the atmosphere of those workings (Dziurzyński & Pomykała, 2006). The mixture fills up the voids in goaf whereby the effective cross-section for the air flow becomes reduced and the local aerodynamic drag increases. The air flow in a given point of abandoned workings occurs in the part not filled up with the sealing mixture (Piotrowski & Mazurkiewicz, 2006). The height of that part can be calculated as the difference between the height of goaf and the height of the body formed by the sealing mixture in that point.

$$h(x,y) = H_z(x,y) - z_g(x,y) \tag{1}$$

where:

$h(x,y)$ — height of the free part of the abandoned workings in the point of the x,y coordinates,
$H_z(x,y)$ — height of the abandoned workings in that point,
$z_g(x,y)$ — height of the filling-up body of the sealing mixture in that point.

Knowing the height of the free part of the abandoned workings in given point the ***VentZroby*** software written in the Strata Mechanics Research Institute of Polish Academy of Sciences (Dziurzyński et al., 2008) can be used for the calculation of local drags in goaf, and then to determine the air flow in abandoned workings which changes as the process of the additional sealing proceeds. Also the distribution of the potential field in the area of the mined longwall affects the air migration directions in the zone of goaf (Dziurzyński & Krauze, 2012).

Hence, in order to know the rate of the distribution of migration of air and gases in the area of abandoned workings it is necessary to know the shape of the body formed in goaf by sealing mixture and its changing with time. This is a complicated issue requiring the application of a mathematical description of the non-Newtonian fluid flow through a porous medium with large pores. A simplified approach to this issue is to assume an approximate shape of the sealing mixture body in goaf and to equalize the volume of that body with the volume of the sealing mixture supplied by a pipeline to goaf with taking account the existing porosity. In this model the impact of the inclination of abandoned workings on the shape of that body has to be taken into account. Such model was presented in the publication (Dziurzyński et al., 2010a). For the modelling of outflow of the ash-water mixture from one pipeline with the possibility of any positioning of the pipeline outlet in abandoned workings was assumed. Currently, a necessity has arisen to work out a model of a simultaneous outflow from a few pipelines, which constitutes a substantial progress in the possibilities of numerical modelling of the inflow of slurry to additionally seal the goaf.

Similarly as in the study (Dziurzyński et al., 2010a), it was assumed that the mixture gradually fills up the goaf forming a body in them the shape of which was approximated with a cone of the generating line angle γ.

Fig. 1 shows diagrammatically a range of the sealing mixture of the volume V_r, supplied by pipelines to an inclined goaf.

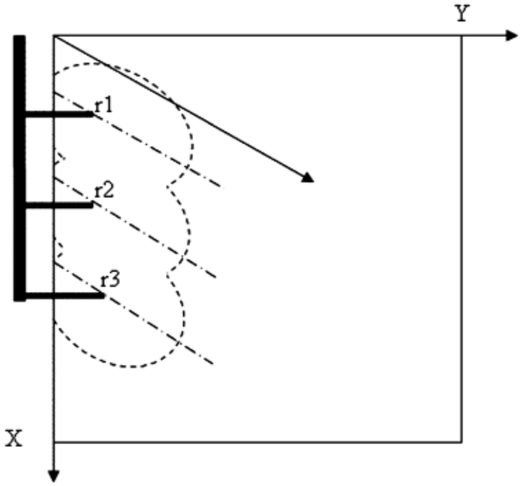


Fig. 1. The range of the ash-water mixture supplied to an inclined goaf with three pipelines

The shape of the body created by the mixture supplied to an inclined goaf is approximated with a cone described with the formula:

$$z = z_0 \left(1 - \frac{r}{r_0} \right) \tag{2}$$

where the height of the cone z_0 and the radius of the cone base r_0 are connected by the relationship:

$$\frac{r_0}{z_0} = \tan(\gamma) \tag{3}$$

The higher the mixture fluidity and the lower its viscosity, the bigger is the angle γ between the cone generating line and its height.

When the cone height z_0 is bigger than the height H_r of the outlet of the pipe supplying the mixture to *f*, then the shape of the mixture body in goaf is approximated with the truncated cone of the height H_r.

The volume of sealing mixture supplied to goaf can be expressed with the formula

$$V_r = \frac{Q_M}{\rho_M} t \tag{4}$$

where:

Q_M — jet of mixture flowing out from the pipe outlet
ρ_M — density of the mixture
t — duration of the mixture supply.

For inclined goaf with different porosity in various goaf places, and when the radius of the range of the mixture is bigger than the distance between the pipe outlet and goaf-sides then the body formed in goaf by the mixture will not be axis-symmetrical, but due to the flow down in the direction of the inclination of goaf the mixture range will be in this direction larger than the radius r_0, whereas it will be smaller in opposite direction. This case is shown in Fig. 2. From this figure the following relationships can be derived:

$$z_a = r\tan(\beta)\cos(\alpha - \alpha_z) \qquad z_b = \frac{r_0 - r}{\tan(\gamma)} \qquad z = z_b - z \tag{5}$$

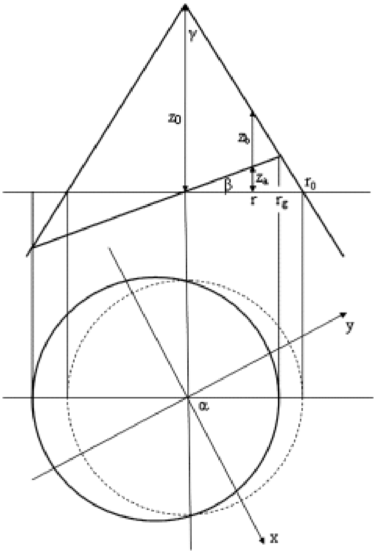


Fig. 2. The body of the ash-water mixture in an inclined goaf

The height of the ash-water mixture body calculated herefrom in the point of the polar coordinates (r, α) is:

$$z(r,\alpha) = \frac{r_0 - r\left[1 + \tan(\gamma)\tan(\beta)\cos(\alpha - \alpha_z)\right]}{\tan(\gamma)} \tag{6}$$

The radius of the mixture body base calculated with the condition $z(r_g, \alpha) = 0$ is:

$$r_g(\alpha) = \frac{r_0}{1 + \tan(\gamma)\tan(\beta)\cos(\alpha - \alpha_z)} \tag{7}$$

where:

r_0 — radius of the circle of the base of the mixture cone on the horizontal plane,
α — angle between the x axis of the coordinate system and the radius r_{01},
α_z — angle between the x axis of the coordinate system and the projection of the vector perpendicular to the plane of the floor of goaf on the horizontal plane,

β — angle of the inclination of goaf,
γ — angle between the height of the slurry body cone and its generating line.

The angle β of the inclination of goaf and the deviation angle α_z as shown in Fig. 2 can be calculated from the values of the spot height assuming the left upper corner of the field of the goaf shown in Fig. 1 as the origin.

To calculate the volume taken by the mixture in goaf the following equation should be used:

$$V_r = \int_{\alpha_0}^{\alpha_0+2\pi} \int_{0}^{r_g} m(r,\alpha) z_g (r,\alpha) r dr d\alpha \tag{8}$$

where V_r *is the volume of the mixture which* has flowed out from the supply pipe, and the integral on the right hand side of the equation expresses the volume of the mixture contained in the body formed in goaf. The integrand is the product of the porosity of goaf $m(r,\alpha)$ in the point of the polar coordinates r and α and the height of the mixture body $z_g(r,\alpha)$ in this point and the radius r. The polar origin is in the point of outlet of the pipe supplying the mixture to goaf, with the coordinates x_r *and* v_r in rectangular coordinates system connected with goaf.

As the slurry mass comes to goaf from a few pipelines at the same time the boundaries of the range of the bodies formed by the slurry in goaf begin to enter in contact. Fig. 3 shows how to make calculations for the boundaries separating the slurry bodies for three pipelines.

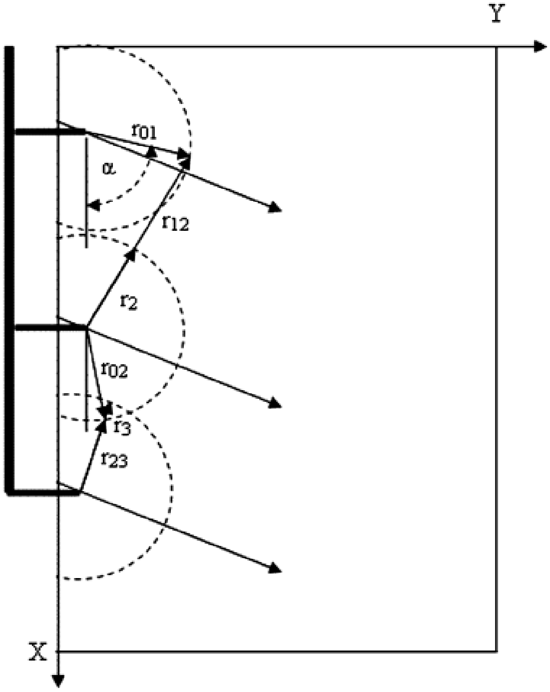


Fig. 3. Determination of the boundary of the range of the slurry in goaf

The boundary between the slurry bodies supplied by the pipeline 1 and 2 can be calculated as follows:

– the radius of the slurry range in goaf

$$r_{01} = \frac{r_{p1}}{1 + w\cos\left(\alpha - \alpha_z\right)} \tag{9}$$

$$w = \tan\left(\gamma\right)\tan\left(\beta\right) \tag{10}$$

where: r_{p1} — the radius of the circle of the base of the slurry cone on the horizontal plane – other symbols as for (7),

– the rectangular coordinates of the point (r_{01}, α):

$$x_1 = x_{r1} + r_{01}\cos\left(\alpha\right), \qquad y_1 = y_{r1} + r_{01}\sin\left(\alpha\right) \tag{11}$$

– the polar coordinates of the point (x_1, y_1):

$$r_{12} = \sqrt{\left(x_1 - x_{r2}\right)^2 + \left(y_1 - y_{r2}\right)^2} \tag{12}$$

$$\alpha_{12} = \arctan\left(\frac{y_1 - y_{r2}}{x_1 - x_{r2}}\right) \tag{13}$$

where:

x_{r1}, y_{r1} — coordinates of the outlet of the pipe 1,

x_{r2}, y_{r2} — coordinates of the outlet of the pipe 2,

– the radius of the range of the slurry in two goaf:

$$r_2 = \frac{r_{p2}}{1 + w\cos\left(\alpha_{12} - \alpha_z\right)} \tag{14}$$

– calculation of the coordinates of the points of intersection of ellipses 1 and 2:

$$r_2 - r_{12} = 0 \tag{15}$$

The results of these calculations are the polar coordinates of the points of the intersection of the ellipses 1 and 2 if the polar origin is the point (x_{r1}, y_{r1})

– coordinates of the point 11: (α_{121}, r_{121}),
– coordinates of the point 12: (α_{122}, r_{122}),

if the origin of polar coordinates is the point (x_{r2}, y_{r2}), then

– coordinates of the point 11: (α_{211}, r_{211}),
– coordinates of the point 12: (α_{212}, r_{212}).

Now the rectangular coordinates of the points 11 (x_{121}, y_{121}) and 12 (x_{122}, y_{122}) can be calculated. Herefrom the parameters of the straight line of the equation $a \cdot x + b \cdot y = 1$ which separates the bodies of the slurry supplied by the pipelines 1 and 2 can be obtained.

$$a_{12} = \frac{y_{122} - y_{121}}{y_{122}x_{121} - y_{121}x_{122}} \qquad b_{12} = -\frac{x_{122} - x_{121}}{y_{122}x_{121} - y_{121}x_{122}} \tag{16}$$

In a similar way the parameters a_{23} and b_{23} of the straight line separating the bodies of the slurry supplied by the pipelines 2 and 3 are calculated.

Now, for the limits of the integration against the radius in the integral (8) for the pipeline no. n the following conditions can be assumed (Tab. 1):

TABLE 1

The radius of the range of the slurry supplied from the pipelines no. 1, 2, and 3
($x_{r\,n}$, $y_{r\,n}$) – coordinates of the outlet of the pipeline no. n; X, Y – goaf dimensions

$n = 1$ $\alpha \le \alpha_{121}$ or $\alpha \le \alpha_{122}$ $n = 2$ $\alpha \le \alpha_{231}$ or $\alpha_{232} \le \alpha \le \alpha_{212}$ or $\alpha \ge \alpha_{211}$ $n = 3$ $\alpha \le \alpha_{232}$ or $\alpha \ge \alpha_{231}$	$r_{g\,n} = \frac{r_{pn}}{1 + w\cos(\alpha - \alpha_z)}$
$n = 1$ $\alpha_{121} < \alpha < \alpha_{122}$ $a = a_{12}$ $b = b_{12}$ $n = 2$ $\alpha_{231} < \alpha < \alpha_{232}$ $a = a_{23}$ $b = b_{23}$ $n = 2$ $\alpha_{212} < \alpha < \alpha_{211}$ $a = a_{12}$ $b = b_{12}$ $n = 3$ $\alpha_{232} < \alpha < \alpha_{231}$ $a = a_{23}$ $b = b_{23}$	$r_{g\,n} = \frac{1 - ax_{r\,n} - by_{r\,n}}{a\cos(\alpha) + b\sin(\alpha)}$
$n = 1{,}2{,}3$ $x_{rn} + \frac{r_{pn}\cos(\alpha)}{1 + w\cos(\alpha - \alpha_z)} < 0$	$r_{g\,n} = -\frac{x_{r\,n}}{\cos(\alpha)}$
$n = 1{,}2\ 3$ $x_{rn} + \frac{r_{p\,n}\cos(\alpha)}{1 + w\cos(\alpha - \alpha_z)} > X$	$r_{g\,n} = \frac{X - x_{r\,n}}{\cos(\alpha)}$
$n = 1{,}2\ 3$ $y_{rn} + \frac{r_{pn}\sin(\alpha)}{1 + w\cos(\alpha - \alpha_z)} < 0$	$r_{g\,n} = -\frac{y_{rn}}{\sin(\alpha)}$
$n = 1{,}2\ 3$ $y_{rn} + \frac{r_{pn}\sin(\alpha)}{1 + w\cos(\alpha - \alpha_z)} > Y$	$r_{g\,n} = \frac{Y - y_{rn}}{\sin(\alpha)}$

For each pipeline the root r_p of the equation:

$$\int_0^{2\pi}\int_0^{r_g(\alpha)} m z_g\left(r_p\right) r\,dr\,d\alpha - Q_{V\,n}t = 0 \tag{17}$$

can be found
where: $Q_{V\,n}$ — the jet of the volume of the ash-water mixture from the pipeline no. n ($n = 1{,}2{,}3$).

Knowing the parameters r_{p1}, r_{p2} and r_{p3} the height z_g of the body filling up goaf in the point (x_i, y_i) can be calculated.

– if $r_{i\,n} < r_g(r_{p\,n}, \alpha_{i\,n})$ then $$z_{g\,n}\left(x_i, y_i\right) = \frac{r_{p\,n} - r_{i\,n}\left[1 + \tan(\gamma)\tan(\beta)\cos\left(\alpha_{i\,n} - \alpha_z\right)\right]}{\tan(\gamma)} \tag{18}$$

where:

n — no. of the pipeline ($n = 1, 2, 3$),
$r_{p\,n}$, α_z, β, γ — as in the formula (6).

Additionally the following condition has to be met:

$$z_g = \min\left(z_{ga}, z_{gb}, z_{gc}\right) \tag{19}$$

where: z_{ga} is given by the formula (18),
$z_{gb} = H_{rn}$ where $H_{r\,n}$ — the height of the outlet of the pipeline no. n,
$z_{gc} = H_z(x_i, y_i)$ where $H_z(x_i, y_i)$ — the height of the goaf in the point (x_i, y_i).

The height of the unfilled part of goaf calculated from the formula (1) after the substitution to the formulas for the lateral drag the network of the of ventilation laterals modelling goaf (Dziurzyński, 1998; Nawrat, 1999) gives us the following values of the drags:

$$R_{x\,i} = \frac{\mu \Delta x}{h_i k_i \Delta y} \qquad R_{y\,i} = \frac{\mu \Delta y}{h_i k_i \Delta x} \tag{20}$$

where:

μ — dynamic viscosity of the air flowing through goaf,
k_i — goaf permeability,
h_i — the height of not filled up part of goaf in the point i of the coordinates x_i, y_i,
Δx, Δy — dimensions of the elements of the network of laterals in the direction x and y.

Taking into consideration the relationship (1) in the formulas (20) we obtain the following relationships:

$$R_{x\,i} = \frac{\mu\left(x_i, y_i\right)\Delta x}{\left[H_z\left(x_i, y_i\right) - z_g\left(x_i, y_i\right)\right]k_i \Delta y} \qquad R_{y\,i} = \frac{\mu\left(x_i, y_i\right)\Delta y}{\left[H_z\left(x_i, y_i\right) - z_g\left(x_i, y_i\right)\right]k_i \Delta x} \tag{21}$$

The above formulas introduced to the modified ***VentZroby*** computer program allow to determine the distribution of the air flow rate in goaf varying with time as goaf is being filled up by the sealing mixture.

3. The water content of the supplied slurry and the thermal processes in the point of fire origin

3.1. Point of fire origin located in goaf

In this discussion, the area of the longwall abandoned workings mined with the roof-collapse technique and filled up with brash and non-extracted coal (Dziurzyński, 1998) is analysed. The oxygen contained in the mixture of air and mine gases enter this area. Due to the processes of the coal self-heating and the accumulation of heat, the temperature in this area increases. The still interesting thing for us is the determination of changes in oxygen concentration, the generation of combustion products, and the level of heat emission. We assume that for the consumption of oxygen in the fire's point of origin decisive is the intensity of the coal combustion process commonly called as the unit combustion rate. By making use of the experiments on the investigation of the dynamics of fire source (Dziurzyński & Tracz, 1994) we assume that the rate of oxygen mass loss for the unit of volume is proportional to the a_p value and the oxygen concentration; hence we have:

$$k_{V\mathrm{O}_2} = \psi a_p C_{\mathrm{O}_2} \tag{22}$$

where:

$k_{V\mathrm{O}_2}$ — the rate of the oxygen mass loss [kg/m^{3}s],
$\psi = \psi[T_{og}(s,t)]$ — proportion coefficient [kg/m^{2}s],
s — current coordinate measured along the line of the mixture flow current,
$T_{og}(s,t)$ — temperature in the fire source point,
$a_p = \dfrac{A_p}{V_{og}}$ — combustion area for the elementary volume [1/m],
V_{og} — volume of fire source point,
A_p — area of fire source point,
$C_{\mathrm{O}_2} = C_{\mathrm{O}_2}(s,t)$ — distribution of the oxygen concentration in the fire source point.

The coal combustion rate k_{VS} can be determined by making use of the oxygen mass loss rate:

$$k_{VS} = \frac{a_p}{k_{\mathrm{O}_2}} \psi C_{\mathrm{O}_2} \tag{23}$$

where: k_{O_2} is the mass of oxygen [kg] needed for the combustion of 1 kg of coal.

The variations in oxygen concentration in the flowing air and fire gases along the fire source area can be determined based on the equation of continuity given in the form:

$$m\frac{\partial \rho_{\mathrm{O}_2}}{\partial t} + \frac{\partial\left(\rho_{\mathrm{O}_2} v_p\right)}{\partial s} = -k_{V\mathrm{O}_2} \tag{24}$$

where:

t — time coordinate
ρ_{O_2} — partial oxygen density,
ρ — the density of the mixture of air and gases, e.g. fire ones,
v_p — the rate of the flow of the mixture of air and gases in the goaf,
m — the porosity of the coal in the place of fire source location.

By applying the mass conservation law to the mixture of air and fire gasses, we have:

$$m\frac{\partial \rho}{\partial t} + \frac{\partial\left(\rho v_p\right)}{\partial s} = M_{ps} - k_{V\mathrm{O}_2} \tag{25}$$

where: M_{ps} [kg/sm^3] is the increase of the mass of the gas combustion products generated during fire for elementary volume. We assume that this increase for the combustion of coal approximately equals to the amount of combusted fuel. Knowing the unit combustion rate given by the formula (23), we can put down:

$$M_{ps} = k_{VS} \tag{26}$$

Taking into account the relationship: $C_{O_2} = \frac{\rho_{O_2}}{\rho}$ where $\rho_{O_2} = \rho_{O_2}(s,t)$ in the formula (24), the partial density of the oxygen in gas mixture [kg/m^3], and the equation (25) and the formulas (23), (22), (26), after transformation we have:

$$m\frac{\partial C_{O_2}}{\partial t} + v_p \frac{\partial C_{O_2}}{\partial s} = -\frac{\psi a_p}{\rho} C_{O_2} \left[1 + C_{O_2} \left(\frac{1}{k_{O_2}} - 1 \right) \right] \tag{27}$$

where: $\rho = \rho(O_2, N_2, CH_4, GP)$ — the density of gas mixture [kg/m^3].

The equation (27) determines the distribution of oxygen concentration as one of the components of the mixture flowing through, depending on the consumption of oxygen mass and the increase of the mass of fire gases.

3.2. Temperature variations in the fire source located in goaf

Now, the heat balance in the volume of the fuel (coal) being burnt remains to be determined, i.e. the fire source point, from which we will find out the temperature of the fire source T_{og}, i.e.:

$$c_{wp} M_p \frac{dT_{og}}{dt} = q_{og} - q_2 - q_3 - q_4 \tag{28}$$

where:

q_{og} — the amount of heat emitted during combustion in unit time in the fire source point,
q_2 — the amount of heat taken over from the fire source point by the flowing air and fire gases,
q_3 — the amount of heat transferred in unit time from the fire source point to the rock mass,
q_4 — the amount of heat being lost for the evaporation of the water contained in the mixture,
T_{og} — temperature in the fire source point,
c_{wp} — specific heat of the burning fuel,
M_p — fuel (coal) seized by fire,

whereby we have:

$$M_p = \rho_w V_{og}\, gr \tag{29}$$

where:

gr — the thickness of burning coal bed in the fire source point,
V_{og} — the volume of fire source point,
ρ_w — coal density.

Then amount of heat emitted during combustion in a time unit in the fire source point is:

$$q_{og} = k_{VS} V_{og} W_d \tag{30}$$

where:

W_d — coal calorific value,
k_{VS} — coal combustion rate.

The heat taken over from the fire source area by the flowing air and fire gases through the section of a substitute workings of the goaf seized by fire in unit time can be expressed by the formula:

$$q_2 = kA_p\left(T_{og} - T\right) \tag{31}$$

where:

k — coefficient for a combined heat exchange by convection and radiation,
T — air temperature.

The heat transferred in time unit from the fire source point to the rock mass:

$$q_3 = -\lambda_s A_p \left.\frac{dT_g}{dr}\right|_{r=r_0} \tag{32}$$

where:

λ_S — coefficient of the heat conductivity for the rock mass surrounding the fire source point,
A_p — fire source point area,
$\left.\frac{dT_g}{dr}\right|_{r=r_0}$ — rock mass temperature gradient at the goaf side adjacent to the fire source where $T_g(r_0) = T_{og}$,
r — the coordinate (radius) directed into the rock mass,
r_0 — the radius of the fire source point.

Because of the supplying of water-ash slurry to goaf the heat lost by the fire source area due to water evaporation. The heat taken over from the fire source area is:

$$q_4 = \Delta m_w\left[c_w\left(t_{wr} - t_w\right) + c_p h\left(t_{og} - t_{wr}\right)\right] \tag{33}$$

where:

t_{wr} — water boiling point, $t_{wr} = 100°\mathrm{C}$,
t_w — temperature of the water in the slurry (e.g. 20°C),
t_{og} — temperature in the fire source area,
c_w — water specific heat $c_p = 4182$ J/(kgK),
$h(t_{og} - t_{wr})$ — Heaviside function.

The mass of the water being supplied to the fire source area at the *dt* time and evaporated

$$\Delta m_w = \kappa \rho_w S_p \left[z_p(k) - z_p(k-1) \right] \tag{34}$$

where:

S_p — dimensions of the fire source area on the plane of goaf,
$z_p(k)$ — the height of the slurry body in the fire source area with the *k* time step,
r_w — water density ($r_w = 100$ kg/m^3)
k — water share in the slurry.

The equations and formulas presented above allow to determine the impact of the flowed in mixture of gases (oxygen) and the humid slurry on the combustion process occurring in the fire source area. This in turn will allow to determine temperature distribution, density distribution, and the loss of the oxygen of the mixture of fire gases flowing through in the area of goaf.

4. Simulation of the spreading of air and methane in the presence of fire after supply of a slurry – examples

The vital purpose of the presented researches is to show the impact of the supplied mineral substances on the processes of self-heating of the coal left in goaf and the development of an endogenous fire in those goaf.

4.1. Numerical model of the area of the longwall 841, initial state

For the simulation of the flow air and methane and the slurry being supplied in the area of the longwall 841, the seam 405/2wg and the adjacent abandoned longwall 841 and their goaf a data base has been developed containing the parameters of the applied mathematical model in the ***VentZroby*** computer program (Dziurzyński, 1998). For the development of the mathematical model of the goaf and longwall-side workings in that area the following data and materials have been used:

- results of the provisional ventilation measurements carried out in the area of the workings of the longwall 841A,
- computer parametric description of the ventilation network in the standard of the data of the system of the ***VentGraph*** computer programs for the condition of its structure and the adjustment of the ventilation in the period of the provisional measurements being carried out,
- design data concerning the mining area, profiles of headings,
- coal seam maps, geological logs of boreholes,
- results of the sensor measurements of methane flow rate and its concentrations recorded by the monitoring system from the period preceding the provisional measurements in the longwall 841A.

On the basis of the analysis of the above materials and data as well as the provisional measurements a numerical model of workings and goaf has been adapted which faithfully illustrated the real structure of workings and goaf and the ventilation system itself (Dziurzyński et al., 2010b).

For the determination of the data characterising the flow in the goaf of the longwall 841A and the abandoned longwall 841B the theoretical model of the permeability distribution and developing of the height of goaf (Dziurzyński, 1998) has been used, as well as the data resulting from the analysis of the 405/2wg coal seam map, geological profiles, and the plan for the longwall mining (geometry of workings, spot heights, mined seam thickness, type of roof rocks).

The substantial action for the developed mathematical model is the determination of the initial state of air and methane spread in the area of the longwall 841A. Fig. 4 presents the amount of air (in rectangles) in the longwall-side workings, the distribution of methane concentration in goaf and the spot height in area nodes. The determined data were adopted for further prognostic calculations.

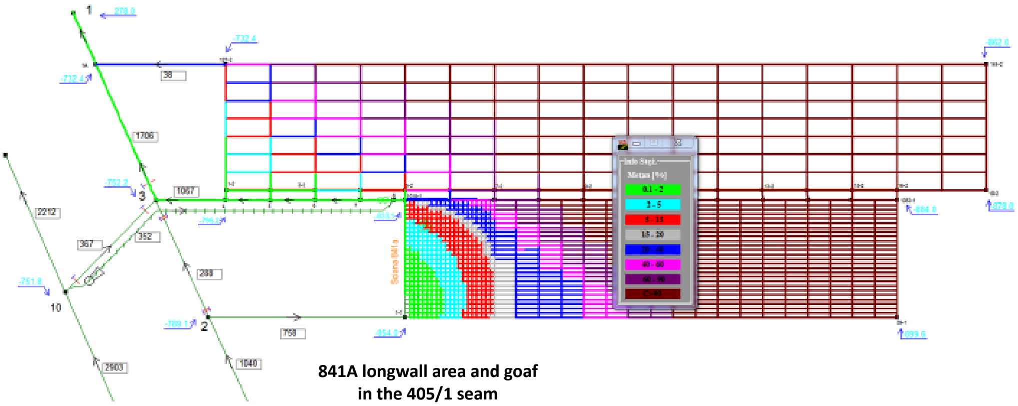
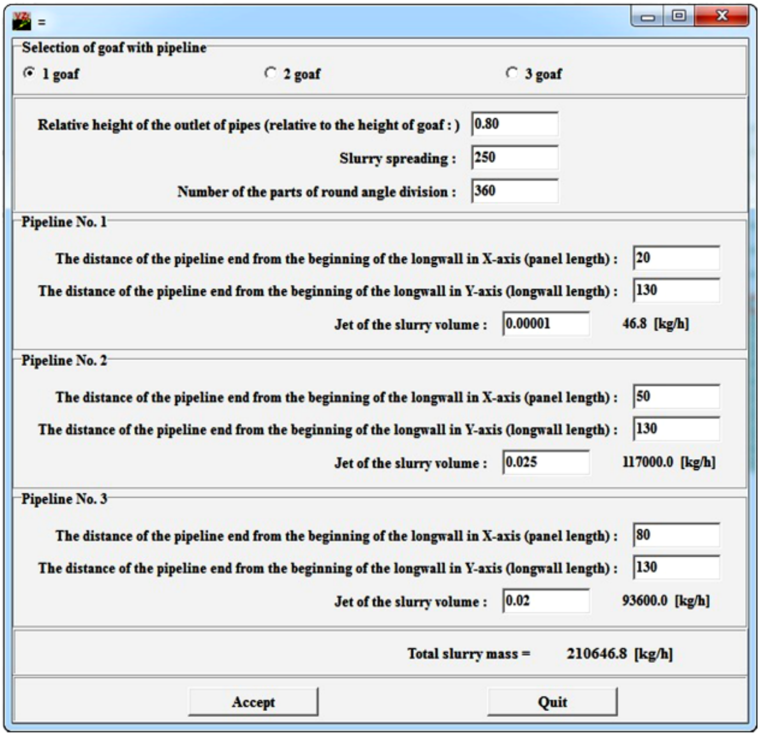


Fig. 4. The distribution of air and methane in the goaf of the 841A and 841B longwalls, the initial state before fire

In accordance with the developed numerical model describing the supply of the slurry to the longwall goaf from a few pipelines (Fig. 1) and the propagation of the slurry in goaf, in Fig. 5 a chart of the ***VentZroby*** program is shown; said chart allows to enter the needed parameters (data) of the adopted numerical model. These parameters (data) characterise the supplied slurry. For the analysed example of the longwall 841A area, the pipeline, due to the elevation configuration, was constructed above the over-longwall heading and put in the heading being abandoned behind the longwall front (panel) at the distance of up to 80 m. The entered parameters are:

- relative height of the pipe outlet relative to the height of goaf,
- slurry spreading,
- number of the parts of round angle division,
- location in coordinates of the longwall goaf of the end of the pipeline supplying slurry, separately for each pipeline,
- the volume jet of the slurry being supplied [m^3/s).

The adopted slurry density allows to determine the jest of the mass of this slurry [kg/h].



Selection of goaf with pipeline

● 1 goaf ○ 2 goaf ○ 3 goaf

Relative height of the outlet of pipes (relative to the height of goaf :) 0.80

Slurry spreading : 250

Number of the parts of round angle division : 360

Pipeline No. 1

The distance of the pipeline end from the beginning of the longwall in X-axis (panel length) : 20

The distance of the pipeline end from the beginning of the longwall in Y-axis (longwall length) : 130

Jet of the slurry volume : 0.00001 46.8 [kg/h]

Pipeline No. 2

The distance of the pipeline end from the beginning of the longwall in X-axis (panel length) : 50

The distance of the pipeline end from the beginning of the longwall in Y-axis (longwall length) : 130

Jet of the slurry volume : 0.025 117000.0 [kg/h]

Pipeline No. 3

The distance of the pipeline end from the beginning of the longwall in X-axis (panel length) : 80

The distance of the pipeline end from the beginning of the longwall in Y-axis (longwall length) : 130

Jet of the slurry volume : 0.02 93600.0 [kg/h]

Total slurry mass = 210646.8 [kg/h]

Fig. 5. Parameters characterising the supplied slurry to the longwall 841A

4.2. Example – fire in goaf versus the supply of slurry

An interesting case for showing the effect of the supply of humid slurry to goaf by at least three pipelines is the performance of prognostic simulations with the application of the ***VentZroby*** program for the situation when in the goaf of the longwall 841A a fire located in the area of the outlet of air from goaf is spreading. The exact place of the fire source area location is shown in Fig. 6. With the red circle (upper part of goaf) the developing fire source point ins marked. The scenario of the development of fire-fighting activity assumes that 52 hours after an increased fire hazard on the outlet from the area was noticed the supply of humid water-ash slurry to the vicinity of the developing fire started.

Due to a great number of data observed it is necessary to apply an option of the ***VentZroby*** program; said option allows to "install" the computer monitoring system. The location of virtual sensors is marked with green circles. The sensors were placed in both the goaf and the over-longwall heading carrying away of the consumed air from the longwall. In the goaf of the longwall 841A we place: a temperature sensor in the fire source area, a carbon oxide concentration sensor behind the fire source point, a temperature sensor of air in goaf 3 m behind the fire source point, and a volume jet sensor behind the fire source point. In the over-longwall heading we place a air and gases mixture flow rate sensor and a carbon oxide concentration sensor at the inlet to the heading.

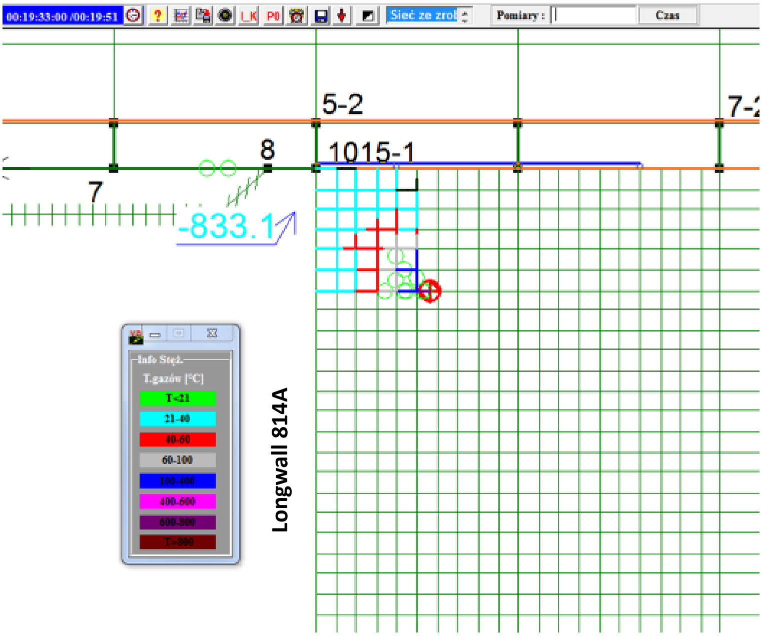


Fig. 6. Temperature distribution in the goaf of the longwall 841A, seam 405.
Bold lines – temperature distribution

The data recorded in the form of sets by the virtual sensors are useful for the purposes of this presentation of the results during the simulation of ventilation process. In the next drawings both the time courses of the variations of the observed parameters and the state of filling up of the goaf with the supplied slurry are shown. First the initial state of the atmosphere in goaf before the slurry was supplied is presented.

Fig. 4 shows that 780 m^3/min of air flows into the longwall, and the outlet from the longwall is being additionally refreshed with the air supplied by the ventilation pipe in volume of 350 m^3/min. The amount of 15.2 m^3/min of methane flows in to the longwall and its goaf. The methane concentration distribution is presented in Fig. 4. In Fig. 6 we can see the carbon oxide concentration distribution after 19 hours of fire development in goaf.

In Fig. 8 we can see the distribution of the temperature of the fire source area in the goaf of the longwall 841A during the development of the burning processes – phase 1 (till the 6th hour), the period of the stabilization of the burning process in the fire source area – phase 2 (from the 6th till the 60th hour). After 52 hours of the fire in goaf the slurry was supplied. The effects of the supply of humid slurry can be seen as the phase 3. where we can observe a substantial reduction of the fire source point temperature (from 63rd till 67th hour).

In Figs. 9 through 13 we can also see the effect of the supply of humid slurry which spreads in goaf as the time passes (Fig. 13).

The effect of the presented filling up of goaf are the changes of the volume jet observed in Fig. 12 in the flow of air and methane mixture in the zone seized by the fire source area in goaf. The filling up of goaf to a certain height of the roof-collapse zone causes temporary changes of

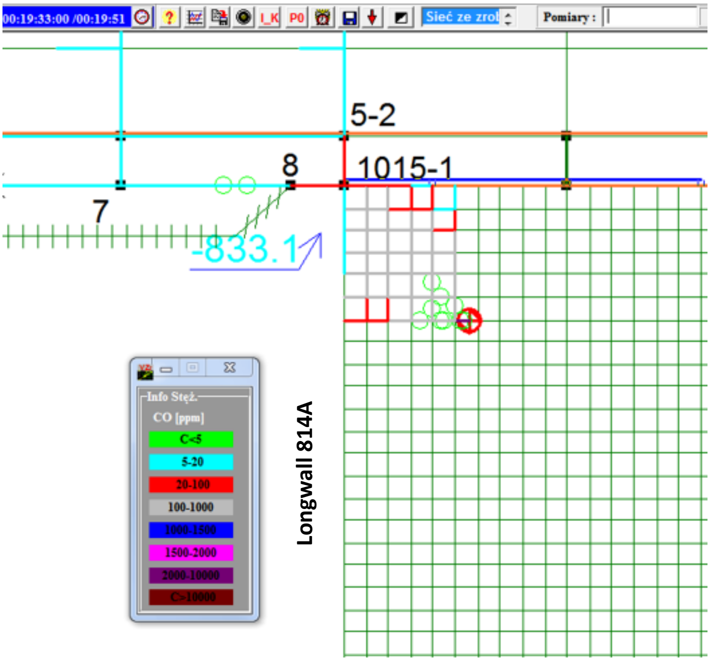


Fig. 7. The distribution of the carbon oxide in the goaf of the longwall 841A.
Bold lines – temperature distribution

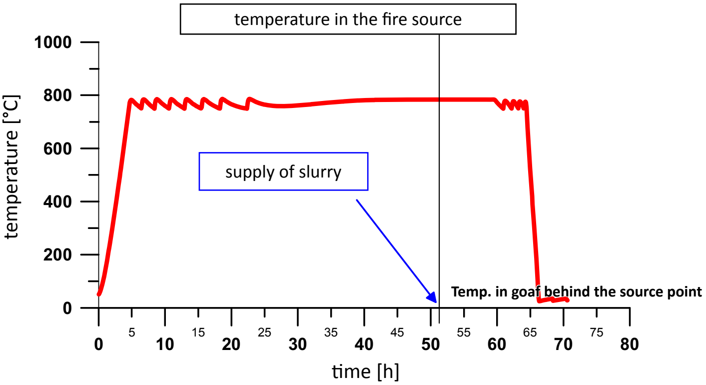


Fig. 8. Temperature variations in the fire source area in the goaf of the longwall 841A
including the conditions caused by the supply of slurry

substitute drags which are modified according to the adopted mathematical model during the prognostic calculations (Dziurzyński, 1998). The distributions of the carbon oxide (Fig. 10 and Fig. 11) and the temporal changes of the volume jet of the air-methane mixture flow presented

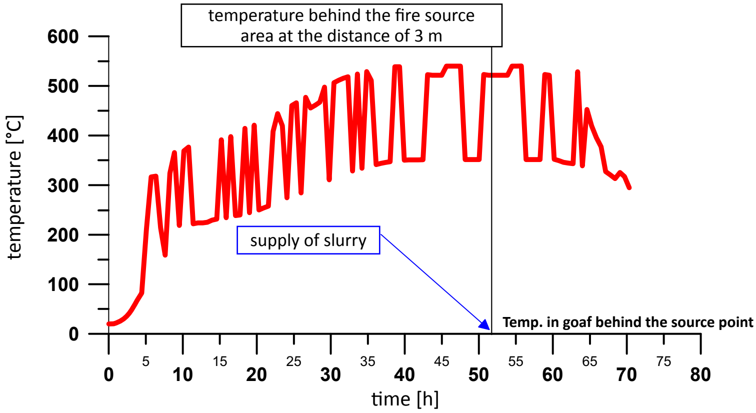


Fig. 9. Air temperature variations behind the fire source area in the goaf of the longwall 841A including the conditions caused by the supply of slurry

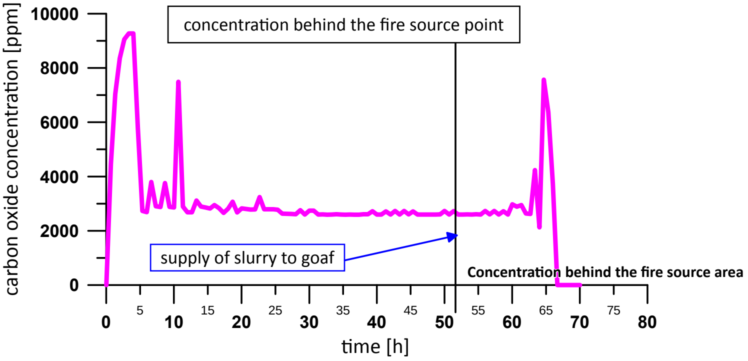


Fig. 10. Carbon oxide concentration variation behind the fire source area in the goaf of the longwall 841A including the conditions caused by the supply of slurry

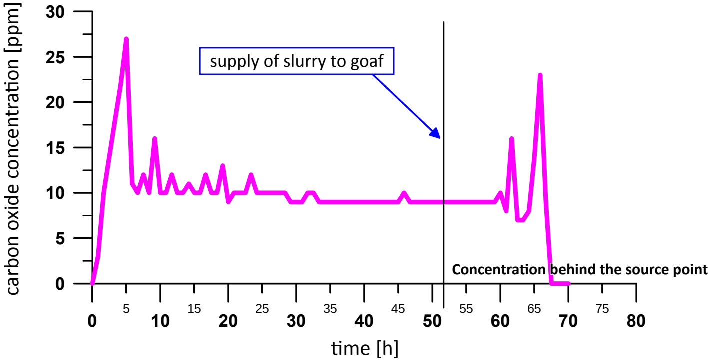


Fig. 11. Carbon oxide concentration variations at the outlet of the longwall 841A area including the state caused by the supply of slurry

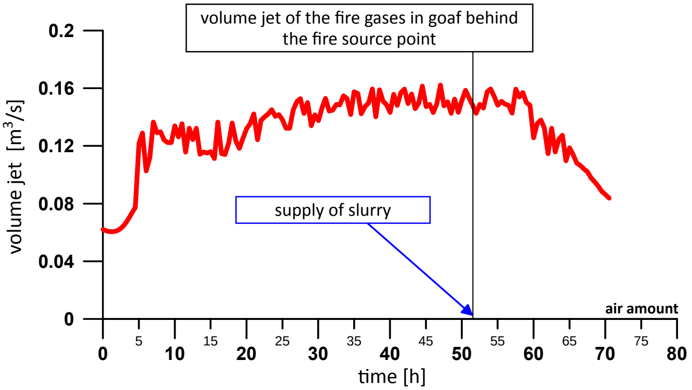


Fig. 12. Volume jet variations behind the fire source area in the goaf of the longwall 841A

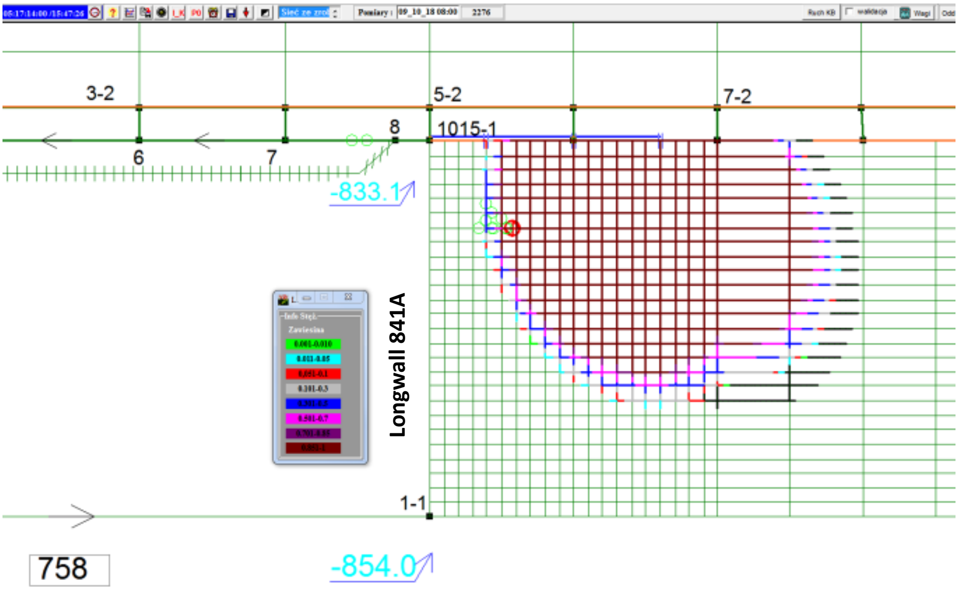


Fig. 13. Height distribution as the measure of the filling up of goaf of the longwall 841A.
The state after 137 hrs of the supplying of slurry.
Bold lines – filling up of goaf

in Fig. 12 clearly show for the impact of the supplied humid slurry on the variations of the observed parameters. It can be stated that the supply of the slurry brought to the extinguishing of the burning processes in the fire source.

5. Summary

The presented mathematical model of additional sealing of goaf by the supply of a humid slurry by three pipelines is based on the balance of volume of the mixture supplied and contained in a slurry body formed in goaf. The shape of this body was assessed with the use of the observation results available in literature (Krause et al., 2009), and the results of model studies. However, the real shape of the body formed in goaf by the slurry flowing in is still not known. The literature on this subject provides also essential information about the basis of the slurry technology applied by the Polish underground mining industry with a particular consideration of fire prevention, which allows the verification of the computer simulation results (Piotrowski et al., 2009). It is also significant that the impact of increased temperature on the properties of ash-water slurries applied in underground mines and the effect of adding cements of various types and slurries of different consistence (Pomykała et al., 2013). The development of the computer simulation methods requires further experimental studies to give credence to the theoretical model of the flow of such mixture through a porous medium, adopted in this study. Such studies would allow to determine the shape of the slurry body depending on the mixture parameters such as humidity, viscosity and fluidity, and the properties of the porous medium. Also, experimental studies should be conducted, leading to a better identification of the mathematical model parameters characterising the flow of the supplied mixtures and fluids in workings and goaf (Krawczyk et al., 2011).

It can be stated that the carried out modification of the mathematical model which describes the process of burning in the fire source area with the consideration of a humid slurry flowing in has been positively verified. The prognostic calculations carried out confirmed a substantial impact of humid slurry supplied to goaf on the changes of parameters of the air mixture flow under the conditions of the coal self-heating processes and fires in goaf. As a supplement to the above, it should be noted that such data as the longwall inclination and the place of slurry supply relative to the inclination of a longwall or the location of the fire source is of great significance for the effectiveness of the applied fire prevention. The further development of the modelling of the phenomena discussed in this paper should be based on the methods of application of the description of the flow of fluid and slurries pursuant to 3D models (Skotniczyny, 2013).

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